Advanced Electromagnetics:
21st Century Electromagnetics

Frequency Selective Surfaces & Metasurfaces

Lecture Outline
- Introduction
- Simple examples
- Grating lobes
- Classifications and comparisons
- All-dielectric frequency selective surfaces
- Metasurfaces
- Conclusions
Introduction

Definition of Frequency Selective Surface

A frequency selective surface is composite material designed to be transparent in some frequency bands while reflective, absorbing or redirecting to others. They are typically flat and composed of metal screen.
Examples

The First Radio Frequency FSS
Physical Mechanisms for Frequency Selectivity

To perform frequency selectivity (filtering), power must be absorbed and/or redirected.

**FREQUENCY SELECTIVE SURFACE**

**ABSORPTION**
Devices are made absorptive by incorporating lossy materials. The absorption can be amplified by also incorporating resonant structures.

**REDIRECTION**
Power is redirected using interference and diffraction. This can be simple reflection, diffraction from a grating or through a guided-mode resonance.

Some Simple Examples
Salisbury Screen

A Salisbury screen was one of the first concepts for frequency selective surfaces and was used by the military to make military vehicles “invisible” to radar.

At the frequency in which the device is resonant, energy is absorbed in the lossy material.

Circuit Analog Absorber

A circuit analog absorber is like a Salisbury screen, but it incorporates periodic structures that amplify the absorption by enhancing the resonance.

Can provide sharper or more tailored resonances
“Perfect” Metamaterial Absorbers


Grating Lobes
**Definition of Grating Lobes**

Frequency selective surfaces are diffraction gratings and will diffract an applied wave into discrete directions if the frequency is high enough.

This is usually seen as a bad thing.

RF engineers call these grating lobes or specular reflection. Optical engineers call these diffraction orders. The are “lobes” due to the bandwidth of the signal.

Grating lobes are a far-field concept. It does not make sense to think about grating lobes within a device.

Grating Lobe Condition

\[ k_i n \sin \theta_m = k_o n_{inc} \sin \theta_{inc} - \frac{2\pi m}{\Lambda_s} \]

\[ n \sin \theta_m = n_{inc} \sin \theta_{inc} - m \frac{\lambda_s}{\Lambda_s} \]

- \( k_i \) = refractive index around diffraction order
- \( k_o \) = refractive index around applied wave
- \( n_{inc} \) = refractive index around incident wave
- \( \Lambda_s \) = interelement spacing (grating period)
- \( m = \cdots, -2, -1, 0, 1, 2, \cdots \)
Onset of Grating Lobes

Although grating lobes can provide a redirection mechanism for frequency selectivity, they are typically viewed as a bad thing.

It is usually desired to operate FSSs at frequencies below a cutoff where there are no grating lobes (no diffracted modes).

Assuming the FSS is operated in air ($n = n_{inc} = 1.0$), this cutoff condition (onset of grating lobes) occurs when $\theta_{c1} = 90^\circ$:

$$f_c = \frac{c_0}{\lambda_x (\sin \theta_{inc} - 1)}$$

$$\lambda_{0,c} = \lambda_x (\sin \theta_{inc} - 1)$$

Classifications and Comparisons
Redirection Mechanisms

**Longitudinal Resonance**
A beam is incident from the top and partially reflects from each of the surfaces. It is the overall interference of the scattered waves that produces the frequency selectivity.

**Transverse Resonance**
An external wave is coupled into a guided mode or surface wave. The guided-mode slowly leaks from the guide due to the grating. It is the interference between the applied wave and the “leaked” wave that produces the frequency selectivity.

**Diffractive**
An applied wave is incident on a grating that scatters it into multiple directions. Frequency selectivity is produced by the inherent frequency dependence of scattering from a grating.

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Multilayer Vs. Single Layer FSS

A tremendous amount of control over the shape of the response of a FSS can be realized using multilayer resonant structures. This approach can combine absorption, longitudinal resonance, transverse resonance and diffraction into a single device.

Multilayer structures are generally more sensitive to angle of incidence.

**FIGURE 1.7.** By using cascaded periodic structures we can obtain a broader top and faster roll-off. However, the bandwidth will vary considerably with angle of incidence.
The above structures are also called “complementary” arrays because they are exact inverses of each other. According to Babinet’s principle for complementary surfaces, their frequency responses will also be exact inverses of each other. In practice, this is not the case because the metals are not perfectly conducting and not infinitely thin. Further, if dielectric is incorporated, these structures can behave very differently.


Planar Vs. Coplanar Arrays

**Dielectric-Metal-Dielectric**
- Large evanescent field
- Less sensitive to dielectric
- More sensitive to external environment

**Metal-Dielectric-Metal**
- Evanescent field confined between plates
- Greater sensitivity to dielectric
- Less sensitivity to external environment
Array Symmetry Considerations

Frequency selective surfaces are essentially planar devices so only consider the five 2D Bravais lattices have to be considered.

For a given element shape, the hexagonal array can fit more elements per unit area than any other symmetry.

Hexagonal arrays have higher “packing density.” Equivalently, the element size can be larger relative to the lattice spacing in a hexagonal array.

The onset of grating lobes tends to be farther out for hexagonal arrays so they are most desirable from this perspective.

Modeling and manufacturing hexagonal arrays can be more difficult.

Fill Fraction Comparison

\[ f = \frac{\pi r^2}{a} \]

\[ f = \pi \left( \frac{r}{a} \right)^2 \]

\[ f = \frac{2\pi}{\sqrt{3}} \left( \frac{r}{a} \right)^2 \]

Hexagonal array provides 15.4% higher fill factor.
Common Element Types

Small relative to wavelength.
Circumference is \( \approx \lambda \)
Common band-pass element.
BW control through line thickness.
Earliest and simplest elements studied.
Large relative to wavelength.
Angle sensitive.
Grating lobes a problem.

Secondary resonances problematic.
Larger elements relative to wavelength.
Small relative to wavelength.
Circumference is \( \approx \lambda \).
Common band-pass element.
BW control through line thickness.
Earliest and simplest elements studied.
Large relative to wavelength.
Angle sensitive.
Grating lobes a problem.


All-Dielectric Frequency Selective Surfaces
Why All-Dielectric?

- Metals can be lossy (especially at optical frequencies)
- Structure may need to be low observable (LO)
- Can be handled more safely in high-voltage environments
- Maybe better suited for high power
- Can be monolithic

Dielectric Mechanisms for Frequency Selectivity

- Stacks of layers
  - Great for optics, but bulky at radio and microwave frequencies
- Naturally absorbing materials
  - May be best approach if it is possible
- Diffraction gratings
- Guided-mode resonance
  - Limited bandwidth
  - Limited field-of-view
  - Typically required to be 100’s of periods
All-Dielectric FSS with Few Periods


All-Dielectric FSS on Curved Surface

All-Dielectric Frequency Selective Surfaces

**Highest Power FSS**
*Operated at over 2.0 GW!*


**Most Broadband All-Dielectric FSS**


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Metasurfaces
Definition

Metasurfaces are essentially planar nonresonant metamaterials.

Ingredients for a definition:
- Subwavelength thickness
- Flat composite structure
- Engineered electromagnetic properties
- Affects waves through modified boundary conditions instead of effective properties

[Image: http://www.innoget.com/0.3072/Method-for-designing-a-modulable-metasurface-antenna-structure]

Metasurfaces Vs. Metamaterials

**Metamaterials** – function is to realize artificial $\mu$ and $\varepsilon$.

$\begin{align*}
\mu & = \mu_{\text{eff}} \\
\varepsilon & = \varepsilon_{\text{eff}}
\end{align*}$

**Metasurfaces** – function is to modify wave fronts arbitrarily.

Metasurfaces can arbitrarily control the following as a function of position:
- Amplitude
- Polarization
- Phase
- Angles (i.e. phase)
- Frequency (nonlinear)
- Reciprocity (nonlinear, anisotropic, etc.)
Standard Law of Reflection

\[ \theta_{\text{ref}} = \theta_{\text{inc}} \]

How Does Phase Accumulate Across Surface?

\[ \phi_{\text{inc}}(x) = k_{x,\text{inc}}x \]
\[ \frac{d\phi_{\text{inc}}}{dx} = k_{x,\text{inc}} \]

\[ \phi_{\text{ref}}(x) = k_{x,\text{ref}}x \]
\[ \frac{d\phi_{\text{ref}}}{dx} = k_{x,\text{ref}} \]
What if the Surface Affected Phase?

$\vec{k}_{\text{inc}} \quad \theta_{\text{inc}} \quad \vec{k}_{\text{ref}}$

$\vec{k}_{x,\text{inc}} \quad k_{x,\text{ref}} - \Phi_{\text{ms}} / k_0$

$\phi_{\text{inc}} (x) = k_{x,\text{inc}} x$

$\frac{d\phi_{\text{inc}}}{dx} = k_{x,\text{inc}}$

$\phi_{\text{ref}} (x) = k_{x,\text{ref}} x - \Phi_{\text{ms}} / k_0$

$\frac{d\phi_{\text{ref}}}{dx} = k_{x,\text{ref}} - \frac{1}{k_0} \frac{d\Phi_{\text{ms}}}{dx}$

Modified Law of Reflection

$k_{x,\text{inc}} = k_{x,\text{ref}}$  

$n_i \sin \theta_{\text{inc}} = n_i \sin \theta_{\text{ref}} = \frac{1}{k_0} \frac{d\Phi_{\text{ms}}}{dx}$
Modified Law of Refraction

\[ k_{x,\text{inc}} = k_{x,\text{trn}} - \frac{1}{k_0} \frac{d\Phi_{\text{ms}}}{dx} \]

\[ n_1 \sin \theta_{\text{inc}} = n_2 \sin \theta_{\text{trn}} - \frac{1}{k_0} \frac{d\Phi_{\text{ms}}}{dx} \]

A Famous Metasurface Element (1 of 2)

A Famous Metasurface Element (2 of 2)

Fig. 5. (A): SEM image of a plasmonic interface that creates an optical vortex, the plasmonic pattern consists of eight regions, each occupied by one constituent antenna of the eight-element set of Fig. 2F. The antennas are arranged so as to generate a phase shift that varies sinusoidally from 0 to 2π, thus producing a helicoidal scattered wavefront. (B): Zoom-in view of the center part of (A). (C) and (D) Respectively, measured and calculated far-field intensity distributions of an optical vortex with topological charge one. The constant background in (B) is due to the thermal radiation. (E) and (F) Respectively, measured and calculated spiral patterns created by the interference of the vortex beam and a co-propagating Gaussian beam. (G) and (H) Respectively, measured and calculated interference patterns with a displaced fringe created by the interference of the vortex beam and a Gaussian beam when the two are slotted with respect to each other. The circular border of the interference pattern in (I) arises from the finite aperture of the beam splitters used to combine the vortex and Gaussian beams. (J) The size of (C) and (D) is 60 mm by 60 mm, and that of (E) to (H) is 30 mm by 30 mm.


Conclusions
Conclusions About FSSs

- Typically want small and tightly packed elements
  - Broadband
  - Robust to angle of incidence
  - Grating lobes less problematic
- The resonant frequency and bandwidth usually depends mostly on the element shape and size, not the array spacing or symmetry.
- The frequency where grating lobes are present depends only on the element spacing and angle of incidence, not the element type (remember FSSs are gratings)
- All-dielectric FSS are an option for niche applications.

Conclusions About Metasurfaces

- Elements are much more subwavelength than with FSSs
- Elements control wave fronts
  - Amplitude
  - Polarization
  - Phase
  - Angles
  - Frequency
  - Reciprocity